GPS Ocean Reflection Experiment on Spartan 251

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ABSTRACT

It has recently been demonstrated that the GPS signal which has reflected from the ocean surface contains useful geophysical data from which the sea surface wind speed and other parameters can be extracted. This can be used for remote sensing, similar to present day use of radar altimeters or scatterometers, but with significantly smaller instrumentation because of the utilization of the existing GPS broadcast signal for illumination. Several campaigns of aircraft experimentation have been completed

demonstrating this technique and reflected GPS data has been reliably collected from 25 km altitude on a balloon. However, there has not yet been a demonstration that the reflected GPS signal can be detected from orbit with sufficient signal to noise ratio (SNR) to make useful remote sensing measurements. A technology demonstration experiment was planned for a Space Shuttle flight in the late 2000 using the Spartan 251 recoverable carrier. This experiment would also have been the first flight validation of the *PiVoT* GPS receiver developed in house at the Goddard Space Flight Center. The "open-architecture" design of this receiver would allow the software modifications to be made which control code-correlator spacing to map out the shape of the reflected signal waveform, which is the most basic data product generated by this instrumentation. A moderate gain left-hand circularly polarized antenna, constructed from an array of off-the-shelf hemispherical antennas was to be used to give approximately 3 to 6 dB of additional gain. Preliminary SNR predictions have been done indicating that this antenna would offer sufficient gain to record waveform measurements. A system level description of the experiment instrumentation, including the receiver, antenna and data storage and retrieval will be given. The visibility of GPS reflections over the mission duration of several hours will be studied, including the effects of the limited beamwidth of the antenna. Spartan 251 has now been postponed with the earliest opportunity in the year 2002. The results of this study, however, have been used to further the define the requirements and expected performance of reflected GPS receivers in orbit. Several other space flight opportunities are being considered based upon this new information.

INTRODUCTION

The reception of ocean reflected GPS signals and their use as a bistatic radar remote sensing instrument for oceanographic research has recently been demonstrated from aircraft. This sensor offers the potential to be a lower cost and simpler complement to existing monostatic scatterometers and altimeters. To provide global coverage, however, an orbiting platform is ultimately required for this instrument. Extension of the present knowledge of reflected GPS phenomenology to orbit presents several complications. For example, the signal to noise ratio at orbital altitudes and velocities is expected to be much lower than that experienced from aircraft. The effect of higher altitudes and velocities is to "spread" the post-correlation power over a wider range of code delays and Doppler frequencies. Before a science experiment can be proposed for a low Earth orbiting receiver, technology experiments should be conducted using a proof of concept instrument to validate the analytical signal models and assess these issues. This paper will present results from one technology experiment proposed on a flight of opportunity on the Spartan 251 Space Shuttle carrier.

MEASUREMENT DESCRIPTION

The physical principle underlying this measurement is illustrated in Figures 1 and 2. Figure 1 shows an ideal specular reflection from a perfectly flat surface. Other than a reduction in power at the reflecting surface, and a change in polarization from right hand circular to predominantly left hand circular, a specular reflected signal is indistinguishable from a direct line of sight signal. This correlation between this signal, and the locally generated identical PRN sequence, decreases to zero at delays of $\pm$ 1 code chip (300 meters for the C/A code) relative to the specular point. The correlation power follows a triangular function, Λ, dependence on relative code delay as shown in Figure 3. As the surface gets rougher, reflections produce signal which reach the receiver having delays that exceed the delay from the specular point. The statistics of the reflecting surface, commonly modeled as either a random distribution of facet slopes or as a random height distribution with a given variance and correlation length, determine the distribution of reflected power as a function of delay. It has been shown [1] that the square of this cross-correlation $Y^2(\tau)$ is the convolution of this distribution in reflected power with the square of the Λ function.

$$Y^2(\tau) = \int_{-\infty}^{\infty} \Lambda^2(\tau - \delta)p(\delta)d\delta \tag{1}$$

In this convolution, $p(\delta)d\delta$ is the received reflected signal in delays between δ and $\delta + d\delta$. This assumes that the correlation length between surface heights is smaller than the size of one code chip, and that the small distribution in carrier frequency resulting from a range of Doppler shifts can be neglected. This latter assumption, which is only appropriate at aircraft speeds and altitudes, will have to be revised for an orbital receiver.

In addition to isolating, or "range-gating" the reflected signal, another effect of correlating with a PRN code generated at one specific frequency is the attenuation of signals which have carrier frequencies different from that of the locally generated code by more than $\pm 1/2T_i$, in which T_i is the pre-detection (or "coherent") integration time. This attenuation follows the $sinc^2$ function.

$$\frac{sin(\pi(f - f_o)T_i)}{\pi(f - f_o)T_i} \tag{2}$$

Retrievals of surface roughness properties are performed by matching the experimentally measured waveform, $Y^2(t)$, against predictions of this waveform shape from analytical models. Recently two such models have been applied to the reflected

GPS application [2], [3]. For details of wind speed retrieval based upon these model, see Komjathy et. al., [4] and Garrison, et. al., [5].

SPARTAN 251 FLIGHT OPPORTUNITY

A flight opportunity for early demonstration of the detection of ocean-reflected GPS signals from Low earth orbit was offered on the Spartan 251 mission. This carrier was originally scheduled for deployment from the Space Shuttle early in the year 2000. The primary payload on Spartan 251 carrier was the eXperimental Satellite System 10 (XSS-10) mission, sponsored by the Air Force Research Laboratory's Space Vehicle Directorate. A secondary objective of the Spartan 251 mission was the flight validation of the *PiVoT* GPS receiver. *PiVoT* is an inhouse GPS receiver development at the NASA Goddard Space Flight Center's Guidance, Navigation and Control Center. As will be described later, the use of an open-architecture design, and a commercial chipset would simplify the inclusion of an experiment to detect ocean reflected GPS signals into the receiver software and flight test plan. The additional hardware necessary to do the ocean reflection experiment would be a nadir oriented left hand circularly polarized (LHCP) antenna and the dedication of one of the four possible RF inputs of *PiVoT* to this antenna. The other 3 RF inputs would be fed by conventional right hand circularly polarized (RHCP) antennas on the zenith oriented face of the Spartan 251 carrier.

Software to process the reflected signal would be fundamentally different, and in fact much simpler than the closed tracking loops used to maintain a pseudorange from a direct GPS line of sight signal.

A concept for the integration of this experiment onto the Spartan 251 carrier is shown in Figure 5. Three RHCP antennas were to be provided, for the possible use as attitude determination. The LHCP antenna was originally planned to be an array of 4 hemispherical GPS antennas. All of these hemispherical antennas have a heritage as aircraft certified antennas, and the LHCP ones are identical models to those used on the previous aircraft data collection flights.

The XSS-10 mission required that the Spartan 251 carrier maintain an inertial attitude. Unfortunately, this attitude would not continuously present the same side of the spacecraft towards the Earth, and hence the reflected GPS experiment would no have been conducted during that portion of the mission. The Spartan mission team, however, had agreed to offer the ocean reflection experiment a period of approximately 5 orbits following successful conclusion of the XSS-10 mission (provided that this operation did not interfere with the objectives of XSS-10). During this period, the Spartan carrier would be placed into a local vertical orientation and the ocean reflection software would be operated on the *PiVoT* Receiver. This period of time, although short, offers an opportunity to demonstrate the first intentional detection of reflect GPS signals from LEO.

As a result of the Space Shuttle scheduling constraints, the XSS-10 experiment was moved from Spartan 251 to an expendable launch vehicle. The Spartan 251 carrier is now tentatively scheduled to support the follow-on XSS-11 mission in 2002. Plans are still in place to host the *PiVoT* flight demonstration and the ocean reflection experiment. As a result of the system studies done to support the Spartan 251 experiment, the requirements for a space based reflected GPS experiment are now better understood. A number of other mission opportunities are presently being pursued based upon this new understanding, and possibly one would predate the 2002 launch of Spartan 251.

SIGNAL MODEL FROM ORBIT

A geometric optics based model was used to approximate the signal level received from a low Earth orbiting receiver from the ocean reflected signal. This model was based upon the work of Cox and Munk [6] and later enhancements ([7], [8]) and was intended primarily for the estimation of post-correlation power level given the placement of a specific set of range-Doppler bins. Other models for this specific signal have been derived, based either upon the wave spectra [2], or empirical models for surface slope probability distributions [3]. These models have been employed for the retrieval of geophysical data recorded using this receiver. For the present assessment of receiver performance, as simpler approximate model was used.

All of these models approximate the diffusely reflecting surface by randomly distributed facets described by a two dimensional probability density of surface slopes. Each of these individual surface facets can reflect specularly, hence the line of a single ray from the GPS satellite, passing through a projected antenna area of A_R follows the path as shown in figure Figure 7. The "tolerance ellipse" in the surface slope plane (β_x, β_y) is given in [ref c+m] by

$$\Delta\beta_x\Delta\beta_y = \frac{1}{4}\pi\epsilon^2 \sec^3\beta_0 \sec\omega_0 \tag{3}$$

for an angular tolerance of ϵ at a surface location defined by β_0 and ω_0. This tolerance is determined by the distance to the receiver and the receiver antenna area ($\epsilon^2 = A_r/(\pi R^2)$). The probability of a facet at this location having a slope within this ellipse, and therefore the probability that a ray incident upon that facet would reflect with the proper geometry to intersect the antenna area A_R is therefore given by

$$P(\beta_0, \omega_0) = p(\beta_x, \beta_y)\Delta\beta_x\Delta\beta_y \tag{4}$$

$p(\beta_x, \beta_y)$ is the probability density of surface slopes. The Gram-Charlier series expansion used in [7], with the corrections from [8] was used for this density function.

If the incident power density of the GPS satellite (Assumed to be at infinity, and therefore to have parallel rays) is I, a differential reflecting area on the surface of dS, located at (β_0, ω_0), would result in a differential power dP at the receiving antenna of

$$dP = P(\beta_0, \omega_0) I \sec\beta_0 \cos\omega_0 dS \tag{5}$$

This power is computed for all points on the surface, an attenuated by Equation (2) to account for the Doppler effects. A surface integration is then performed over elliptical annuli representing fixed delays with respect to the direct signal. This is multiplied by 0.63 to account for the approximate reflectance of water and results in the power density, $p(\delta)$ of Equation (1). Finally, the convolution in Equation (1) is computed over a number of delay "bins", τ, to estimate the post-correlation signal power.

Results of the predicted reduction in signal power (in comparison to the direct line of sight signal) following reflection from the ocean surface at wind speeds of 4 meters/sec and 12 meters/sec is given in Figure 8. This figure shows the received power at an altitude of 350 km from the surface reflection, measured relative to the direct signal power and assuming a unity gain receiving antenna. The GPS satellite is directly overhead of the receiver and the two satellites have coplanar velocity vectors.

RECEIVER ARCHITECTURE

This experiment was to be realized primarily as software modifications to the existing *PiVoT* receiver. An LHCP antenna was the only specialized hardware required. The *PiVoT* receiver is being developed in house at the NASA Goddard Space Flight Center for use as a space flight C/A code navigation and attitude determination receiver as well as a test bed for research on GPS algorithms. This receiver was designed to be modular and used the industry standard compact PCI bus. The baseline configuration of this receiver, which was to have been provided to Spartan 251 project, would use a StrongArm processor card and a four RF input receiver card based upon the Mitel (formerly GEC Plessey) 2010 RF front end, and two 2021 correlator chips. Each of the 2021 chips has 12 pairs of early and late correlators. This architecture would allow a great deal of flexibility in the design and implementation of low-level GPS algorithms such as new tracking loop designs and mapping of the post correlation power in the code delay and Doppler frequency space, which is the raw measurement required for the detection of ocean reflected signals.

The Mitel system was also the same chipset used on all of the aircraft and balloon experiments to date, and therefore much of the software architecture could be reused. The additional requirement existed to account for larger Doppler shifts between the direct and the reflected signals to be encountered in orbit due to the curvature of the Earth and the apparent motion of the receiver normal to the reflection plane. This effect was never significant at aircraft altitudes and velocities and consequently all of the receiver designs to date ignored the difference in Doppler frequency between the direct GPS signal and the reflection.

A block diagram of the *PiVoT* receiver configured for this experiment is shown in Figure 4.

It was assumed that all 24 correlators (available by splitting the 12 pairs up and using early and late independently) present on one of the 2010 chips would be dedicated to the ocean reflection experiment. These would be fed through the down-looking antenna. The desired selection and spacing of these correlators in terms of relative code delay and Doppler frequency with respect to the direct signal will be determined from the previous model for signal strength.

It was assumed that the other correlator chip, fed by the direct antenna would operate up to 12 tracking loops using an early and late delay lock loop discriminator. This would would be utilized to generate pseudorange measurements and, if possible, a point position solution. These raw measurements would be processed through the use of the GEODE real time navigation filter [9] embedded into the *PiVoT* receiver computer [10]. This filter would estimate the orbit elements of Spartan 251 from the direct GPS signal. From estimations of receiver position and GPS satellite positions, made at most every 0.1 second but possibly as infrequent as every few seconds if processing speed is limited, the code phase for the reflection channels would be commanded to a range of discrete predicted delays near the specular point. From orbit, it is important that this location be computed using a model for the shape of the Earth's surface which has at least the fidelity of the WGS-84 ellipsoid.

Doppler must also be compensated for, and this is done first by referencing the Doppler shift to the specular point, and the commanding a offset by fixed 500 Hz "bins" if required. For the Spartan 251 experiment, all 24 bins were to be set at the Doppler offset for the specular point, and separated in code delay from -1 chip to +11 chips relative to a specular reflection from the WGS-84 ellipsoid.

The pre-detection integration time of the 2021 chipset is fixed in the hardware at 1ms. Although this could be conceivably increased up to 20 milliseconds (limited by the data bit transition) by accumulating inphase and quadrature samples before they are squared and added, this operation would lead to an increase in the complexity of the software. This mission was a flight of opportunity, and hence significant rewrites of the receiver software in this manner, which may require more careful timing between the direct and the reflected channels, was not determined to be feasible.

Furthermore, the correlation time of the noisy reflected signal is not known. It is assumed that over times much longer than the 1 ms, the reflected electric field would behave as Rayleigh scattering, and hence will have a phase which is a uniformly distributed random variable, and magnitude that is a Rayleigh distributed random variable. It it furthermore assumed that for the 1 ms, the reflecting surface is "frozen" and the relative motion of the GPS satellites and the receiver can be perfectly compensated for by tracking of the direct signal. Where the transition between these two extremes lies, is presently unknown. The effect of a breakdown of the frozen surface assumption is that performing the so-called "coherent" integration of I and Q separately for longer and longer times would at some point result in lower as opposed to higher signal to noise ratio. As long as the frozen surface assumption holds, a constant value for the "phase" of the reflected signal can be assumed over the 1 ms time. Theoretically, under these conditions, the signal to noise ratio would increase linearly with coherent integration time.

The sum squares $I^2 + Q^2$ can also be "incoherently" added, with a resulting theoretical improvement in SNR, by the square root of the number of samples. (assuming that they are all uncorrelated). An estimate of the maximum useful incoherent integration time can be found from the smallest diameter of the area on the ocean's surface which contribute to the reflected signal power. Katzberg and Garrison (1996) show that the semi minor axis of the ellipse enclosing all delays less the δ is

$$b = \frac{\sqrt{2\delta h \sin\gamma}}{\sin\gamma} \tag{6}$$

For a satellite overhead ($\gamma = 90\,\text{deg}$), the 12-chip range of delays that can be recorded will correspond to a radius of 50 km on the ocean surface. Given that the orbital speed at 350 km altitude is 7.7 km/sec, one can conclude that 6.5 seconds of data can be averaged without the risk of losing geophysical data.

Table shows an estimate of the signal to noise ratio expected from reflections off of a surface in the presence of 12 meter/sec winds. From Figure 8 this power ranges down to as low as -30 dB relative to the direct signal. Following a post-detection integration (incoherent) of 0.1 seconds (giving an SNR improvement of 10 dB), up to 6.5 sec of data can be averaged according to the sampling considerations given earlier which will result in another +9 dB improvement in SNR. The potential increase in SNR found be using a higher gain antenna is considered next.

To date, only hemispherical GPS antennas have been used for the aircraft and balloon experiments. From a satellite altitude of 350 km, a true hemispherical antenna would not have any advantage because the visibility of reflected signals are limited by the angular diameter of the Earth. Furthermore, satellites with angles of incidence above approximately 70 degrees are less useful for the wind speed retrieval. If a beam width of 63 deg is allowed which would cover all satellites above 70 deg. incidence at that altitude, then an antenna gain of 5.6 dB can be realized. As the later visibility simulations will show, a nadir-orientated antenna could be used even with a (relatively) narrow beam width of ± 30 degrees and there will still be a strong probability of detecting a reflected signal. With this in mind, an antenna gain of 11.7 dB (which corresponds to a beam width of 30 degrees) could be used. Details of the selection and design of the antenna proposed for Spartan 251 is given in then next section. Three antenna gains are therefore considered; 3 dB, representative of a hemispherical antenna; 6 dB representative of an antenna limited by the angular diameter of the Earth; and 12 dB representative of the 30 deg beamwidth antenna.

It is assumed that all of the 1 ms samples are incoherently averaged for the 0.1 sec reporting interval, and subsequently passed through a moving average filter with a time constant of 6.5 sec. These result in total SNR estimates in each range bin of 7 dB, 10 dB and 16 dB, respectively. It is expected that these SNRs are sufficient to determine the characteristics of the waveform shape from a reflected signal.

Finally, the power in all range and Doppler bins can be summed. This could be used for the search and detection of an ocean reflected signal and an estimate of the total power, without recovering any structure of the waveform itself (which would contain most of the science information). If it is assumed that these powers are uncorrelated (which is uncertain) then that will increase the signal to noise ratio by $\sqrt{24} = 4.9$ or 6.9 dB. This measurement would therefore give a SNR between 14 dB and 23 dB depending upon the antenna gain selected.

Power estimates, and the assumed beamwidth influence other aspects of this mission design, such as the satellite selection and visibility to be discussed next.

ANTENNA PERFORMANCE

Given the above specifications for an antenna gain of 11 dB, it was next desired to design a low cost antenna which would be compatible with the Spartan 251 carrier. A source of off the shelf hemispherical antennas (designed and certified for aircraft use) was already identified. These were inspected and once the surface paint was removed, were accepted for flight on the Space Shuttle (the paint posed an out gassing problem). However, at that time no commercial moderate gain antenna was identified.

An array of of these hemispherical was constructed as shown in Figure 6. Theoretically, this arrangement, with proper phasing adjusted by the phase shifters, can produce a bore-sight gain of 12 dB. This array was assembled and tested using an L band 1575.42 carrier in the anechoic changer of the Antenna and Tracking Section at Goddard Space Flight Center. The measured gain pattern relative to a that measured for the hemispherical antenna alone (using carrier only) is shown in Figure 9.

When used with a re-broadcast GPS signal under uncontrolled conditions, however, an approximate gain of only 3dB relative to the hemispherical antenna was realized. This was determined to be the result of the preamps in the four antennas adding noise as well as signal. When used with a carrier, this amplification will increase the SNR. However with spread spectrum GPS signals, already below the noise floor, the premplifier would amplify both the signal and the noise, effectively adding nothing to the SNR.

One possible modification would be to use 4 passive antennas, with a single preamp. However, it is not know if the cable losses through the phase shifters and the power combiners would reduce the signal to noise ratio sufficiently such that this arrangement would offset any benefit of using a single pre amplifier. The plan for Spartan 251, however, was already determined to use the four-element array and as such we would have to operate with the lower gain (approx. 6 dB), according to the calculations in Table this would result in a 10 dB final SNR for 6.5 s incoherent integration. An SNR of 17 dB would be provided for the detection only question, ie. summing of all 24 reflected bins to provide an estimate of total reflected power. As pointed out earlier, these SNRs are expected to be sufficient for the detection of a reflected signal, and probably high enough to retrieve some representation of the waveform shape.

One advantage of the four-element array is that proper adjustment of the phase shifters between the antenna could be used to set a fixed orientation of the main lobe of the gain pattern. This has been considered as a technique to avoid potential multipath from the large grapple fixture located nearby (see Figure 5). It could also be used to orient the beam in the direction of most probable detection of a reflection (see Figure 13 and Figure 14).

Such an antenna would probably have to be fabricated, but could be done as a modification to an existing design for a aircraft antenna. A typical design would be a helix. Through adding additional turns to the helix, the gain could be increased.

This is the design being pursued for other space flight missions in the planning phases at this point, and may be substituted for the array antenna on the rescheduled Spartan 251 mission in 2002.

Higher gain would either require some ability to steer the antenna, or would limit the reception to signals at very high elevations. The former could result in a much more complicated and expensive system, requiring control of the antenna phasing from the GPS receiver itself, based upon the predicted satellite elevations. One advantage of the reflected GPS instrument over conventional backscatter instruments was identified as its ability to use small, unsteered antennas, without the additional complications. It may be possible, nonetheless, to leverage design work presently done for null-steerable or beam-steerable antennas for other applications to this mission concept.

ORBITAL SAMPLING

A study was conducted to determine the frequency which reflections can be observed, and the distribution of these reflections is azimuth, and nadir angle (γ as defined as in Figure 10). Two typical shuttle inclinations were assumed: the 28.5 deg minimum inclination, and the 57 deg inclination planned for the Space Station. An altitude of

350 km was used. Reflections were identified by searching for a visible GPS satellite which met the conditions for a specular point, using a typical GPS satellite constellation collected on the day of March 30, 1998 and a simulation of 7 days of Shuttle orbits. The orbit of both the receiver and the GPS transmitters was simulated for 7 days, and the statistics on reflected points was collected at 30 second intervals.

A land mass map, based upon a 1/4 degree grid, was used to mask out specular points which would have occurred over land. The results of the first 500 seconds of these simulations are shown in Figure 11 and Figure 12. These plots illustrate the opportunity for reception of a reflected signal over the planned duration of this phase of the Spartan 251 mission. The visibility simulation was done to determine the expected duration of a reflected signal being received within the beamwidth of the antenna described above. One advantage of the phased array design is that the main lobe of the beam can be "steered" or set to a non-nadir orientation by the proper adjustment and calibration of the phase shifters. With this in mind, an alternative to the assumed nadir-orientation would be to set the main beam toward a higher elevation, determined by the greater probability of detecting a reflected signal.

Histograms showing the relative distribution of the reflected signal nadir angle (γ) are shown in Figure 13 and Figure 14. From this information, it may be better to have the beam focused toward 55 deg off-nadir. This will constrain the azimuth, however there is a possibility to allow the Spartan carrier to change attitude in order to acquire a GPS reflection.

Assuming a beam width of $\pm 30^o$, an nadir-oriented antenna over this 7 day simulation was found to receive a reflected signal 64 % of the time at the high inclination (57 deg.) and 69 % of the time at the low inclination (28.5 deg.).

Figure 15 and Figure 16 plot the lowest nadir angles observed from all satellites visible during the first 500 minutes of this simulation. As these plots both show, there are times in which a satellite would be visible within the narrow beamwith of this antenna for a long enough period of time for the data to be averaged.

CONCLUSIONS

As a result of planning for a flight of opportunity on the Spartan 251 carrier, the requirements for a technology experiment demonstrating the acquisition of ocean-reflected GPS data from LEO have been better defined. With the expected signal to noise ratio of 7 dB to 16 dB for antenna gains of 3 dB to 12 dB, respectively, this experiment was found to be feasible with small modifications to the GPS receiver software and the addition of a minimal amount of hardware.

Incident Power	-160 dBW	-160 dBW	-160 dBW
Background Radiation	-205 dB/W	-205 dB/W	-205 dB/W
Incident SNR	45 dB-Hz	45 dB-Hz	45 dB-Hz
Reflection Loss	-30 dB	-30 dB	-30 dB
1ms Coherent Integration	-30 dB	-30 dB	-30 dB
Antenna Gain	+3dB	+6 dB	+12 dB
SNR Following Correlation	**-12 dB**	**-9 dB**	**-3 dB**
0.1 sec. Incoherent Integration	+ 10 dB	+ 10 dB	+ 10 dB
6.5 sec. Moving Average	+ 9 dB	+ 9 dB	+ 9 dB
SNR In Each Delay Bin	**7 dB**	**10 dB**	**16 dB**
Σ All 24 Bins	+ 7 dB	+ 7 dB	+ 7 dB
SNR Of Total Power Estimate	**14 dB**	**17 dB**	**23 dB**

Table 1: Signal To Noise Ratio Estimates for Different Antenna Gains

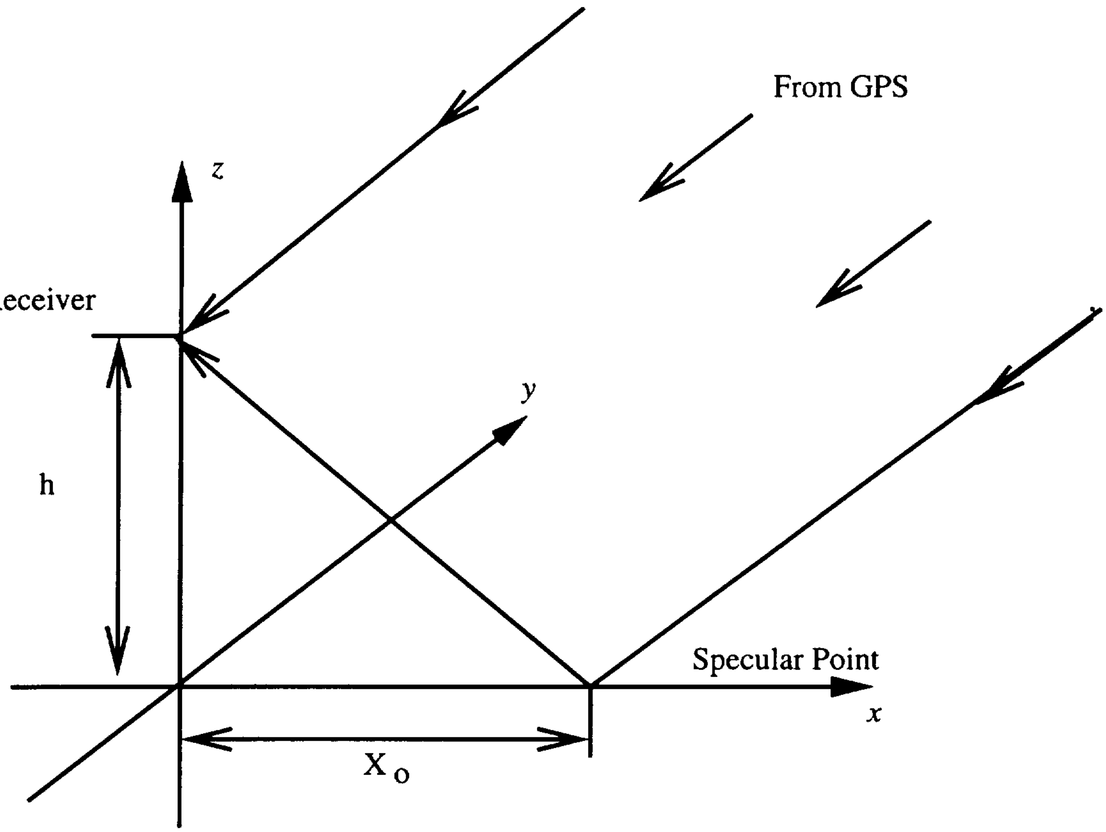

Figure 1: Specular Reflection Geometry.

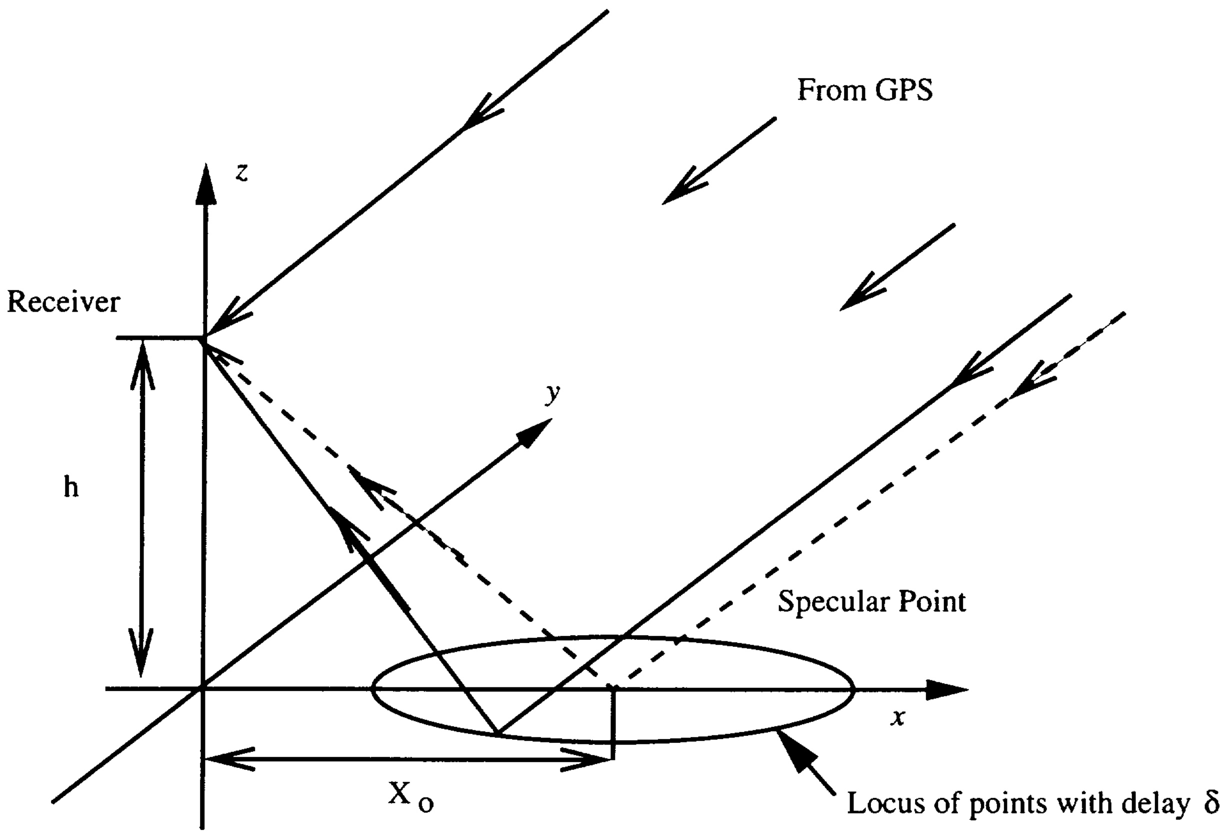

Figure 2: Diffuse Reflection Geometry.

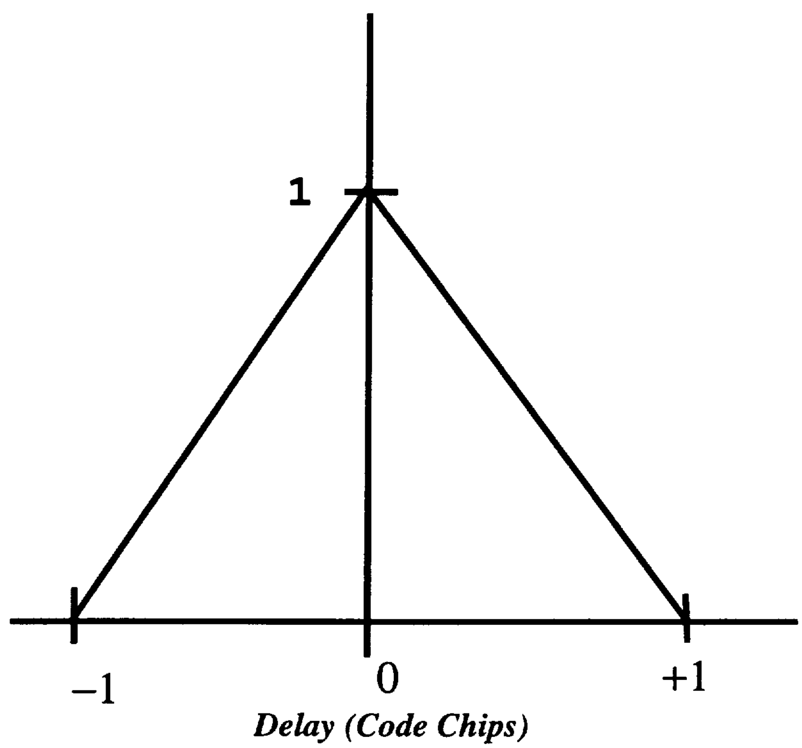

Figure 3: Ideal Correlation For Pseudorandom Noise (PRN) Codes.

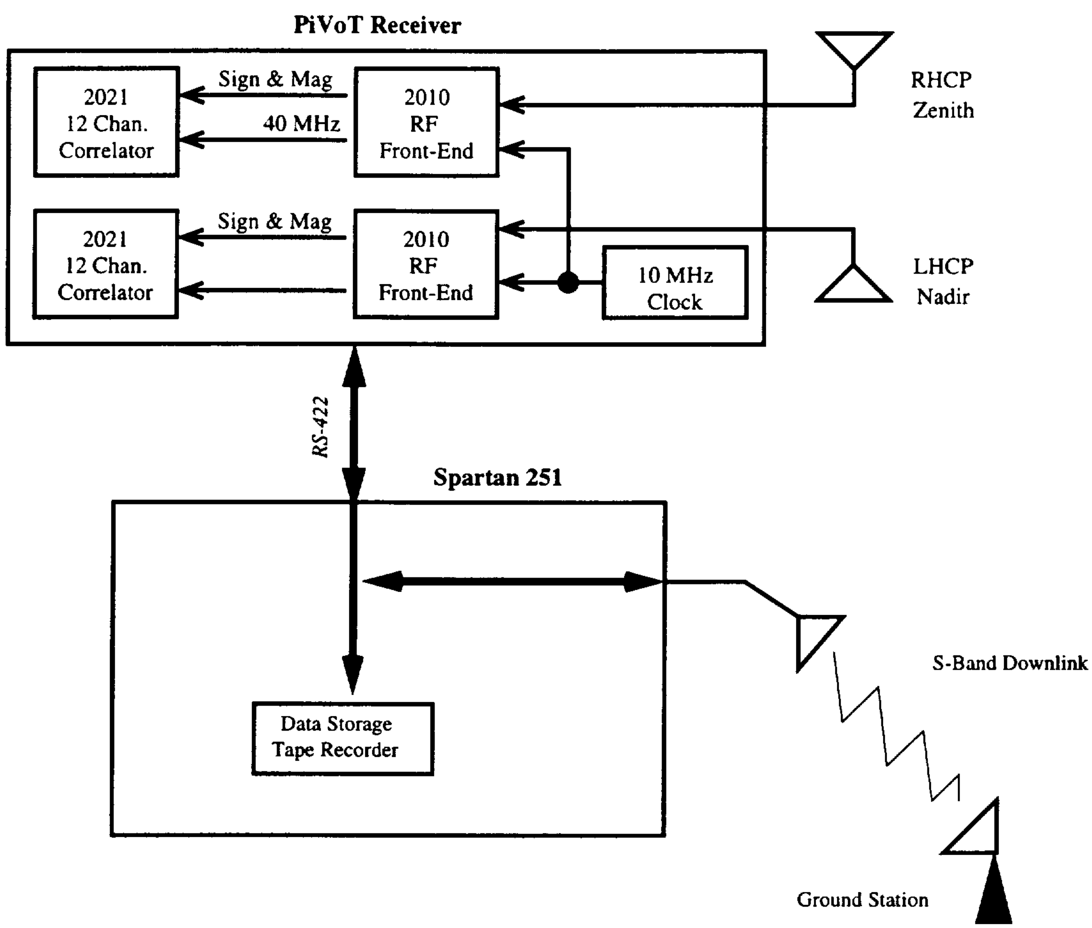

Figure 4: Operation of the GPS Ocean Reflection Experiment on the *PiVoT* Receiver

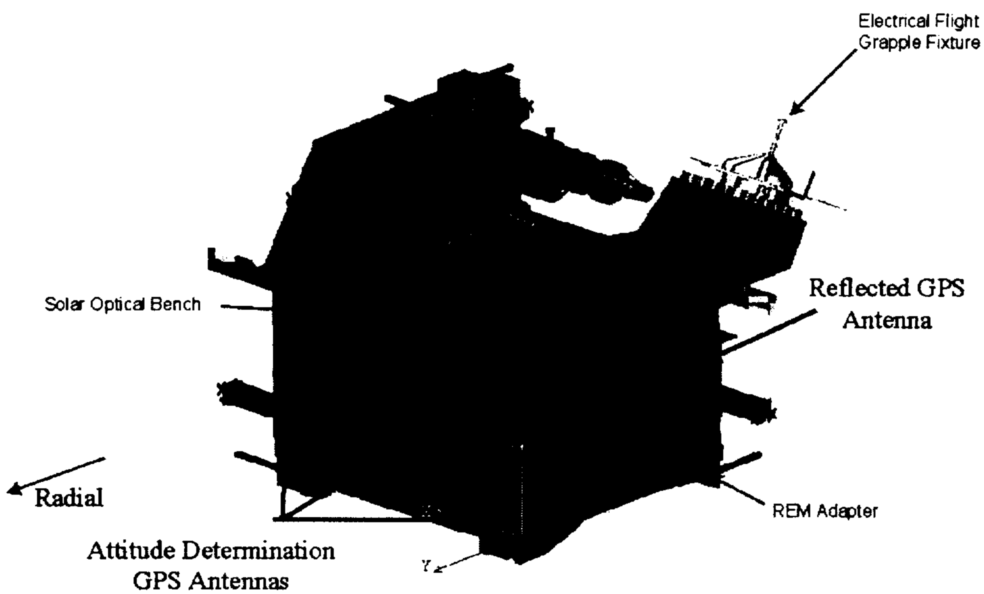

Figure 5: Concept for Integration of GPS Ocean Reflection Experiment on the Spartan 251 Carrier

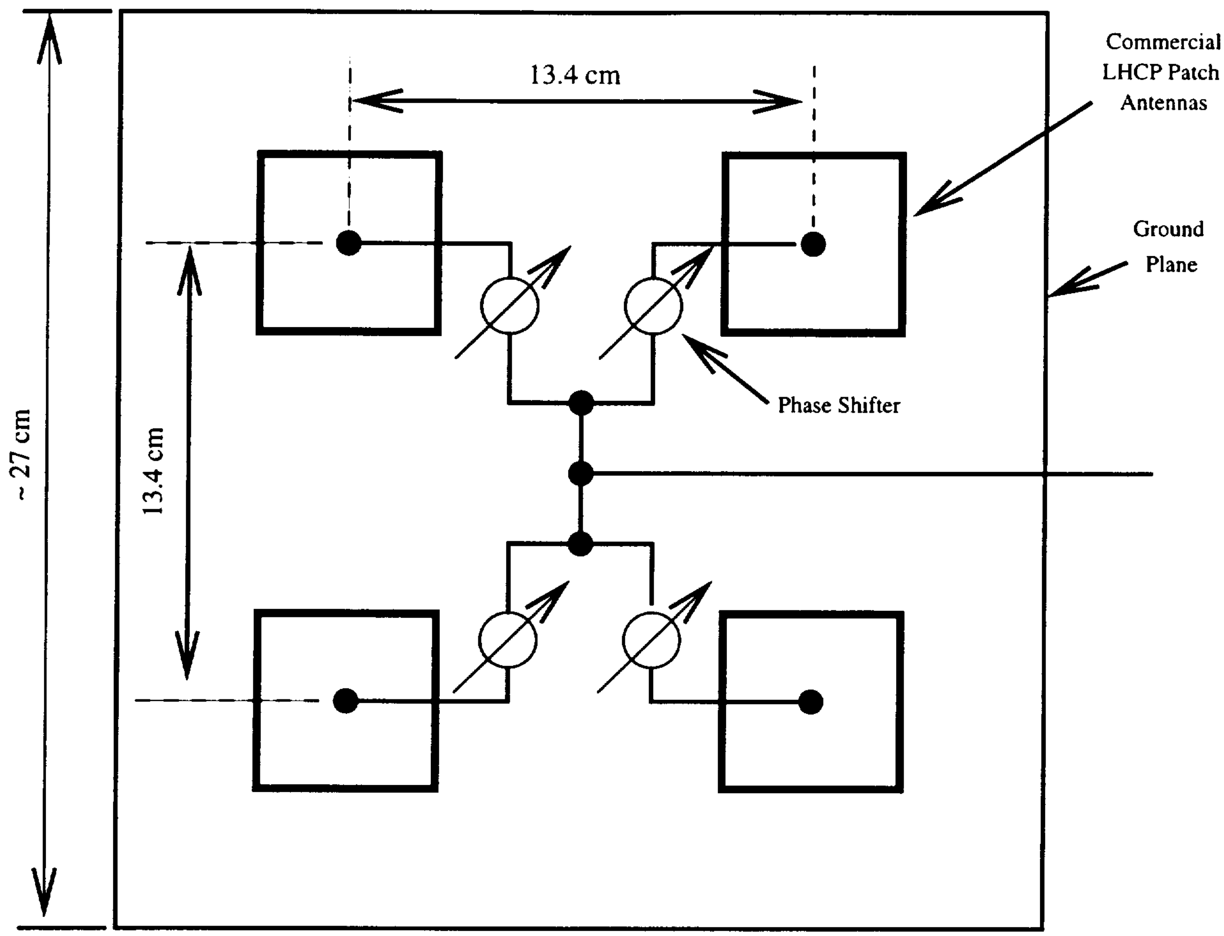

Figure 6: LHCP Antenna Array

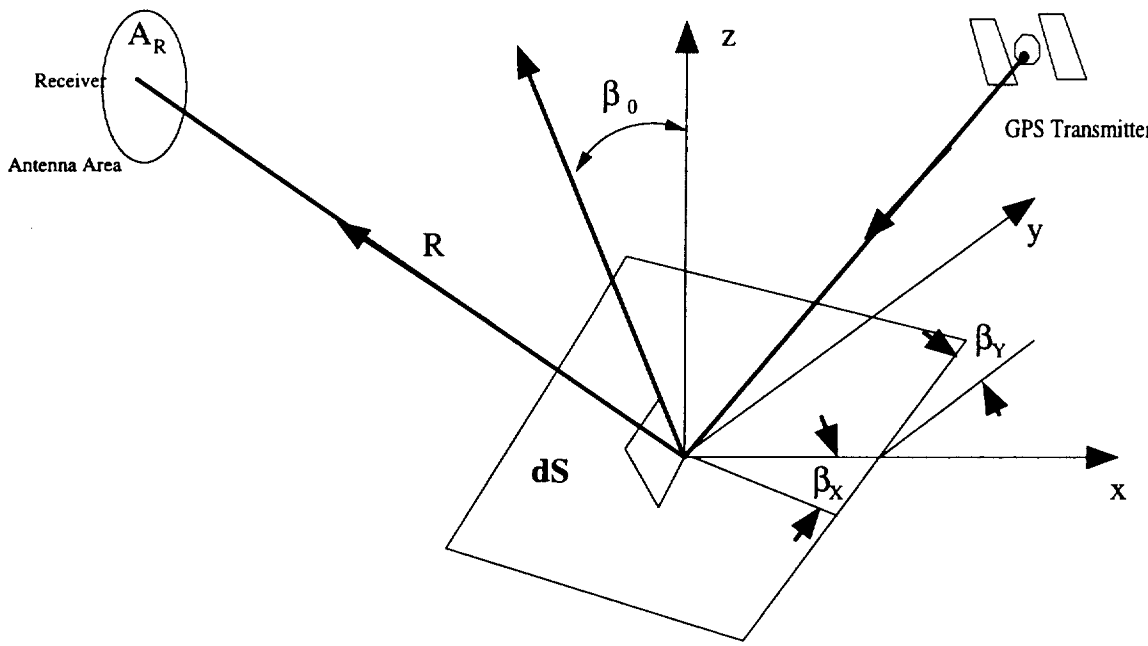

Figure 7: Reflection Geometry for Signal Model

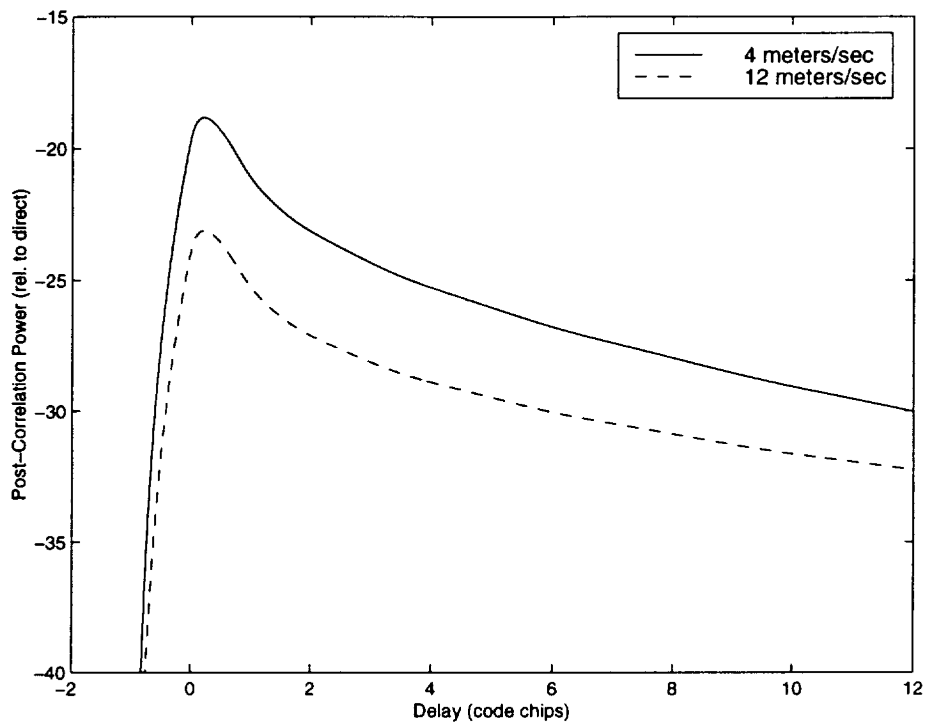

Figure 8: Theoretical Prediction of Reflected Power (Post-Correlation)

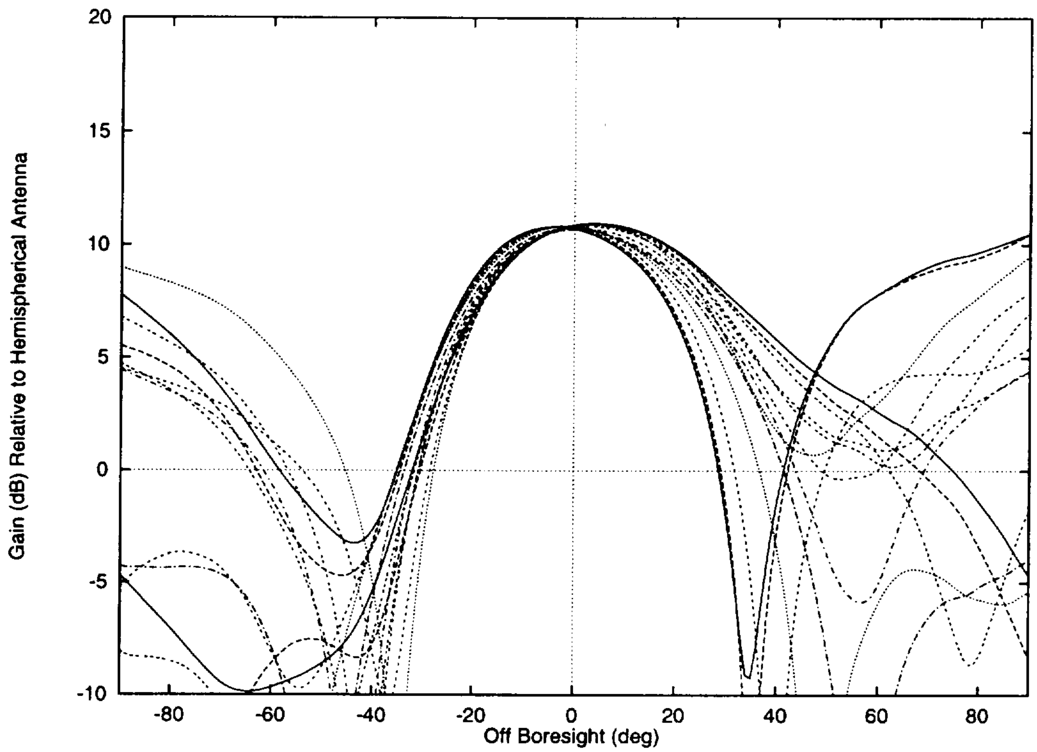

Figure 9: LHCP Antenna Array Gain Pattern (1575 MHz Carrier Only, Relative to Hemispherical Antenna Alone)

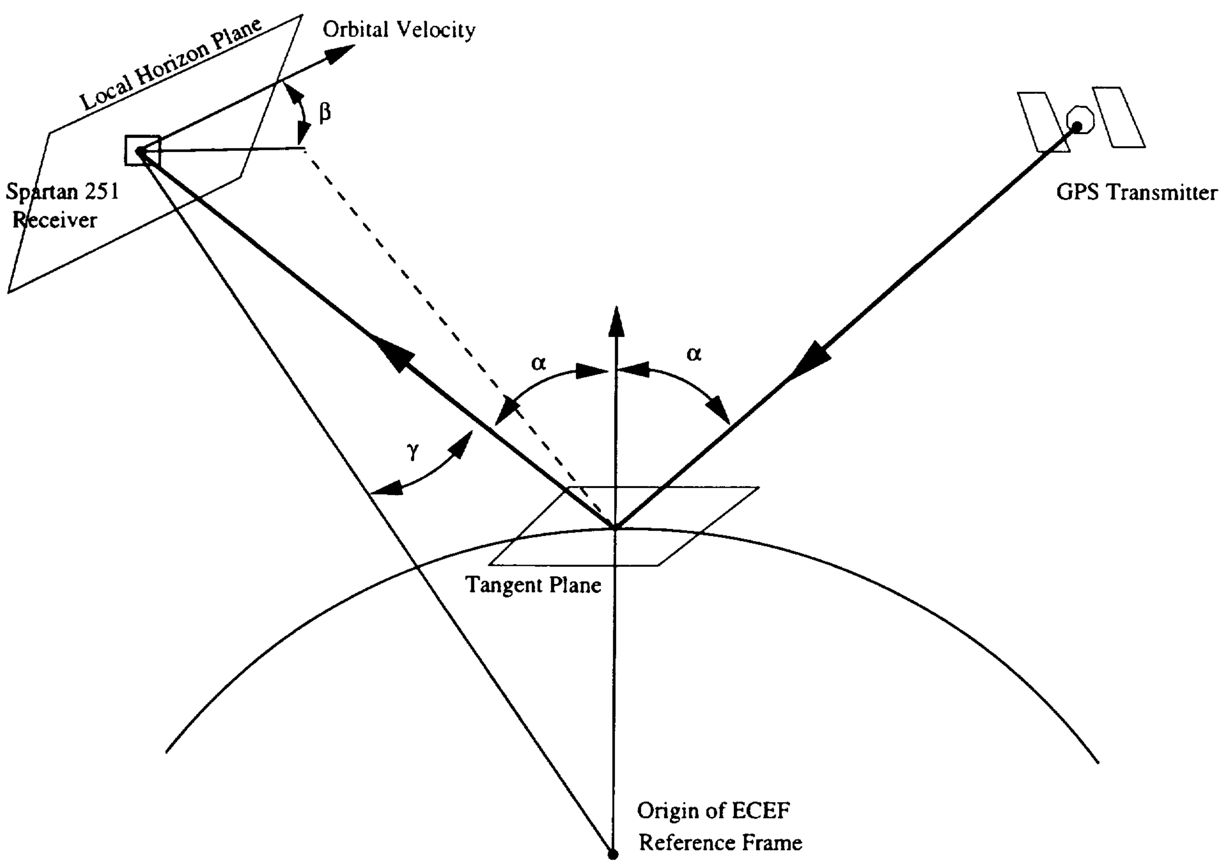

Figure 10: Geometry of GPS Bistatic Reflection from a Spherical Earth

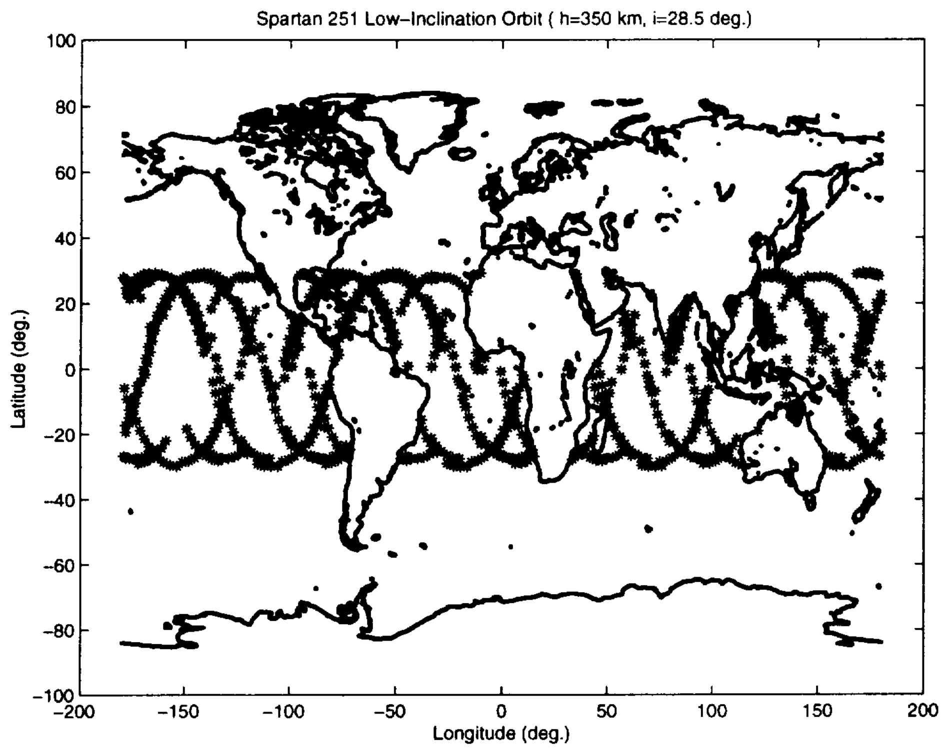

Figure 11: Location of Specular Points, Assuming ± 30 deg Beamwidth, 500 minute Simulation

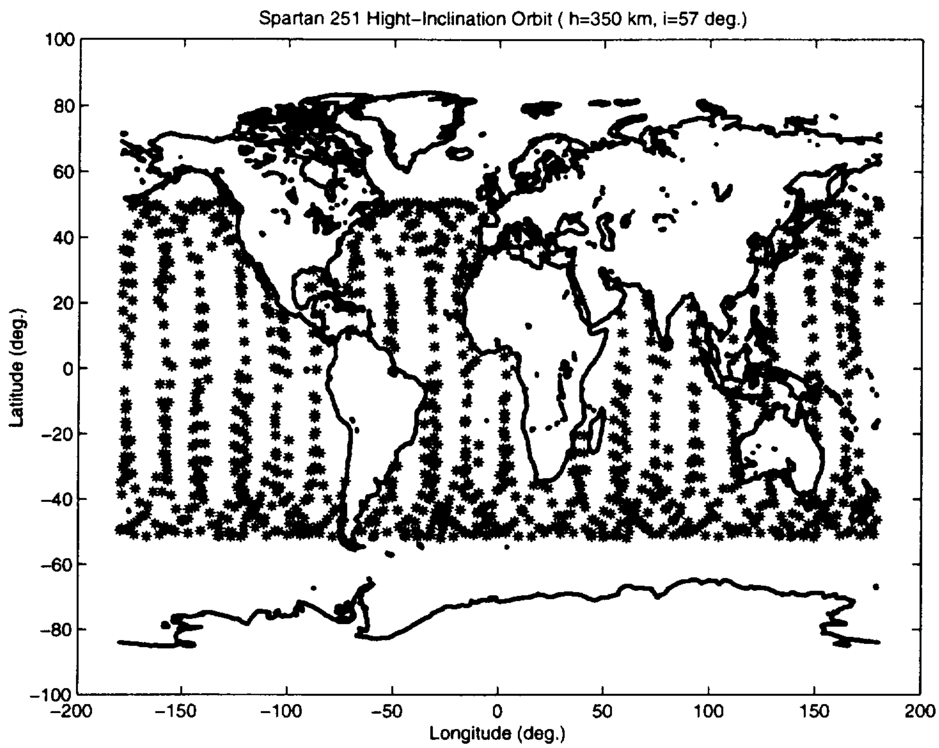

Figure 12: Location of Specular Points, Assuming ± 30 deg Beamwidth, 500 minute Simulation

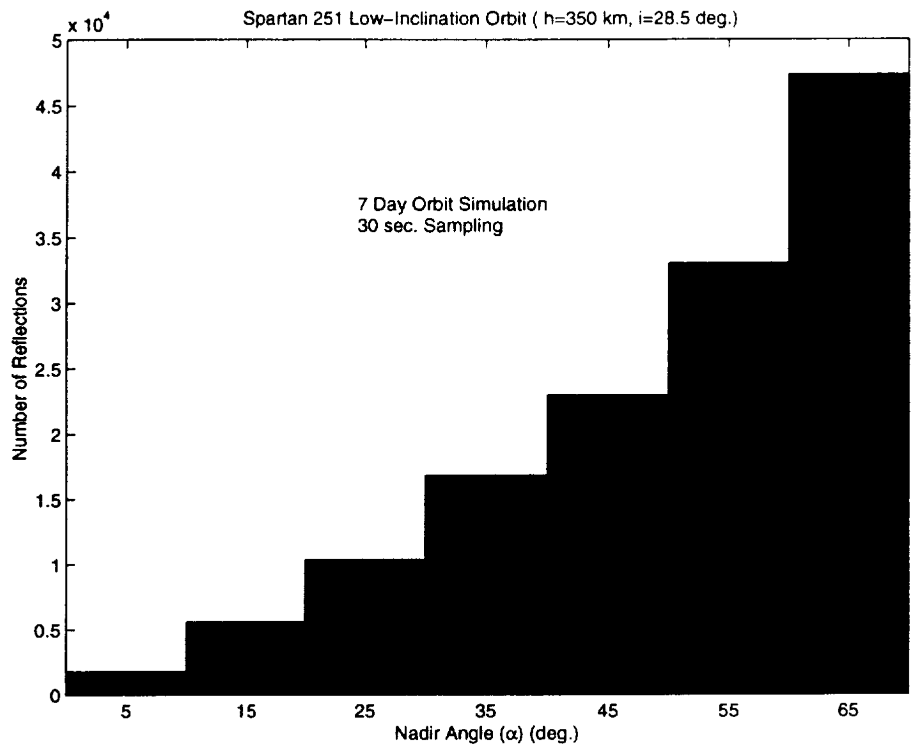

Figure 13: Histogram of Nadir Angles (γ) for 7 Day Simulation of the Spartan 251 Orbit

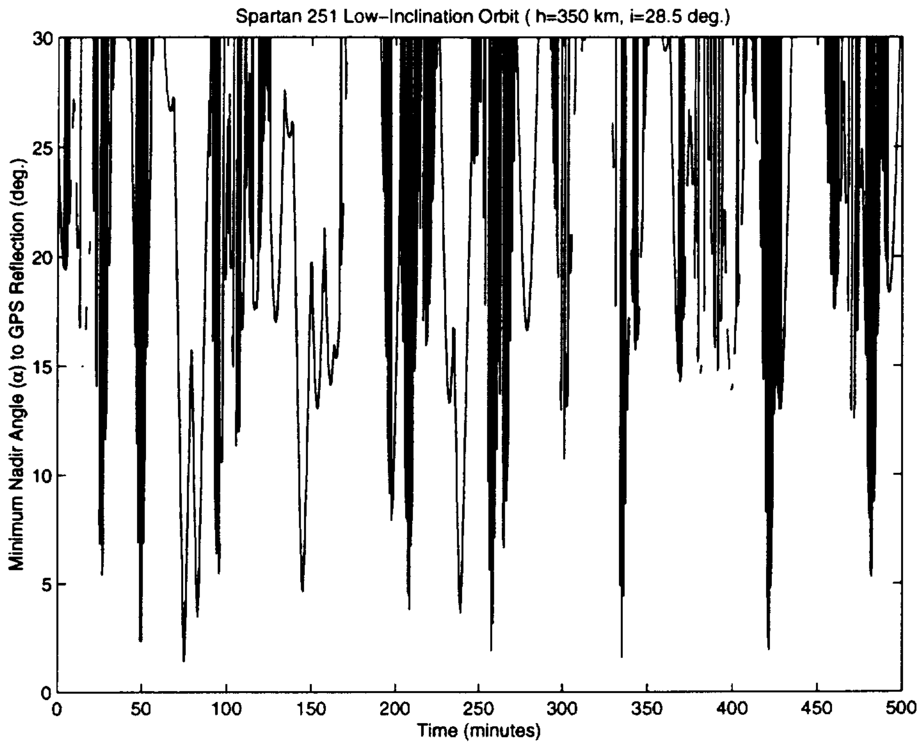

Figure 15: Minimum Nadir Angles (γ) for 500 seconds of Spartan 251 Orbit.

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